

## Article

# The Development of a Framework for the Integrated Assessment of SDG Trade-Offs in the Sundarban Biosphere Reserve

Charlotte L. J. Marcinko <sup>1,\*</sup>, Robert J. Nicholls <sup>2</sup>, Tim M. Daw <sup>3</sup>, Sugata Hazra <sup>4</sup>, Craig W. Hutton <sup>5</sup>, Chris T. Hill <sup>5</sup>, Derek Clarke <sup>1</sup>, Andy Harfoot <sup>5</sup>, Oindrila Basu <sup>4</sup>, Isha Das <sup>4</sup>, Sandip Giri <sup>4</sup>, Sudipa Pal <sup>4</sup> and Partho P. Mondal <sup>4</sup>

<sup>1</sup> School of Engineering, University of Southampton, Southampton SO17 1BJ, UK; d.clarke@soton.ac.uk

<sup>2</sup> Tyndall Centre for Climate Change Research, University of East Anglia, Norwich NR4 7TJ, UK; Robert.Nicholls@uea.ac.uk

<sup>3</sup> Stockholm Resilience Centre, Stockholm University, Kräftriket 2B, SE-106 91 Stockholm, Sweden; tim.daw@su.se

<sup>4</sup> School of Oceanographic Studies, Jadavpur University, Jadavpur, Kolkata 700032, India; sugata\_hazra@yahoo.com (S.H.); oindrila.basu@gmail.com (O.B.); ishad2012@gmail.com (I.D.); sandip1989ju@gmail.com (S.G.); sudipa.3019@gmail.com (S.P.); partho.iirs@gmail.com (P.P.M.)

<sup>5</sup> School of Geography and Environmental Sciences, University of Southampton, Southampton SO17 1BJ, UK; ch9@soton.ac.uk (C.W.H.); cth@geodata.soton.ac.uk (C.T.H.); ajph@soton.ac.uk (A.H.)

\* Correspondence: cljm1g08@soton.ac.uk



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**Abstract:** The United Nations Sustainable Development Goals (SDGs) and their corresponding targets are significantly interconnected, with many interactions, synergies, and trade-offs between individual goals across multiple temporal and spatial scales. This paper proposes a framework for the Integrated Assessment Modelling (IAM) of a complex deltaic socio-ecological system in order to analyze such SDG interactions. We focused on the Sundarban Biosphere Reserve (SBR), India, within the Ganges-Brahmaputra-Meghna Delta. It is densely populated with 4.4 million people (2011), high levels of poverty, and a strong dependence on rural livelihoods. It is adjacent to the growing megacity of Kolkata. The area also includes the Indian portion of the world's largest mangrove forest—the Sundarbans—hosting the iconic Bengal Tiger. Like all deltaic systems, this area is subject to multiple drivers of environmental change operating across scales. The IAM framework is designed to investigate socio-environmental change under a range of explorative and/or normative scenarios and explore associated policy impacts, considering a broad range of subthematic SDG indicators. The following elements were explicitly considered: (1) agriculture; (2) aquaculture; (3) mangroves; (4) fisheries; and (5) multidimensional poverty. Key questions that can be addressed include the implications of changing monsoon patterns, trade-offs between agriculture and aquaculture, or the future of the Sundarbans' mangroves under sea-level rise and different management strategies. The novel, high-resolution analysis of SDG interactions allowed by the IAM will provide stakeholders and policy makers the opportunity to prioritize and explore the SDG targets that are most relevant to the SBR and provide a foundation for further integrated analysis.

**Keywords:** delta; sustainable development; SDG; integrated assessment; India; mangrove; socio-ecological systems; integrated assessment modeling; climate change

## 1. Introduction

The United Nations' 2030 Development Agenda is a set of internationally agreed upon goals that provide a comprehensive strategy to guide policy and action toward sustainable development [1]. The 17 Sustainable Development Goals (SDGs) and the 169 targets, universally adopted by all UN member states, recognize that human development and well-being is dependent on the Earth's natural systems and that neither socio-economic

nor environmental goals can be achieved in isolation [2]. As such, many of the thematic areas of the SDGs (e.g., health, education, economic growth) are strongly connected to each other through multiple targets [3] and these interactions and complex interlinkages need to be considered to achieve the 2030 Agenda [4]. Insufficient understanding or consideration of these interactions can result in incoherent policy making and inadvertent adverse effects of policy in one sector on another. However, possible synergies, conflicts, and trade-offs between individual SDGs and development pathways have received relatively little attention [5,6].

As an example, SDGs relating to food security (SDG2), poverty and inequality (SDG1, SDG10), and life in water and land and climate change (SDG14, SDG15, SDG13) are potentially competing in many socio-ecological circumstances [7]. Therefore, there are many instances where there will be synergies (+ve interactions) and trade-offs (−ve interactions) between the targets related to these goals. Nilsson (2017) identified that target 2.3, which calls for the doubling of agricultural production and income of small-scale farmers, has a number of potential trade-offs with targets related to the protection of terrestrial ecosystems and biodiversity (SDG 15) and the reduction of marine nutrient pollution (SDG target 14.1). Conversely, synergies were found with reduction of poverty (SDG target 1.2) and building resilience of the poor (SDG target 1.5). Recognizing and understanding such potential interactions between SDGs and their targets is essential to promote better informed decision making in complex socio-ecological systems and delivering the 2030 Agenda. However, due to their scope and application across all UN member states, the interactions between SDGs and their targets are not fixed. These interactions will depend on multiple factors including geographic location, natural resources, levels of infrastructure, institutions, and cultures [2]. Furthermore, although SDG targets are assessed at a national level, the governance of SDG-related issues and implementation of policy often occurs on subnational regional or local levels. Therefore, to gain significant understanding of the interactions between SDGs requires consideration of not only the level at which policies are implemented but also the appropriate scales to study the biophysical, social, and economic systems of interest.

Globally, low- and mid-latitude deltas are a major focus for human settlement with a recent estimate of more than 300 million residents in 2017 [8]. It has been recognized for over 30 years that these areas are threatened by sea-level rise and subsidence [9–12]. However, sea-level rise is only one factor shaping deltas, and multiple drivers are acting on a range of scales [13]. For example, regional catchment management, including dam construction, generally reduces water and sediment input and water extraction, causing sediment starvation and increased subsidence (e.g., [14–16]). Hence, delta regions are widely experiencing rising water levels, inundation, salinization, and erosion, enhancing hazards and impacting rural livelihoods and food security. Further, most large delta regions in the global south are experiencing significant rural-to-urban migration and growth of cities, following wider global trends [12,17], and their economies are also developing rapidly with agriculture in relative decline [18]. Given their large, dense, and often poor populations, deltas are critical to achieving the SDGs and all the issues discussed above are relevant.

Analyzing SDG interactions and developing coherent and policy-relevant socio-ecological strategies remain challenging with hardly any demonstrations. Participatory integrated assessment approaches bringing together different spheres of knowledge with relevant stakeholder engagement have great potential to support such a process [7,13,19,20]. As part of an integrated assessment tool, this paper aims to design a modeling framework, including participatory input, that can be used to explore socio-ecological interactions related to several SDGs in a deltaic environment. It is applied to the Sundarban Biosphere Reserve (SBR), India, an important part of the Ganges-Brahmaputra-Meghna (GBM) delta. The modelling framework is able to assess multiple delta-specific biophysical and socio-economic processes under a range of explorative and/or normative scenarios, allowing present and future trade-offs and synergies between SDGs and their related targets to be assessed. In this case, it has the potential to inform strategies across multiple sectors, such

as sustainably reducing poverty, improving food security, and conserving mangrove forests within an area of international ecological importance.

The paper is structured as follows. Section 2 introduces the study area—the Sundarban Biosphere Reserve—and briefly describes present conditions in this complex human–natural system. Section 3 shows the overall integrated assessment approach to examine trade-offs and synergies for the selected SDGs. Section 4 explains the operational approaches for the SBR. Within this section we describe (1) stakeholder participation and policy analysis to identify key drivers, interactions, and trends within the system; (2) the key issues to explore within the SBR, as determined by likely synergies or trade-offs in policy areas and stakeholder interests; (3) scenarios of change to address future uncertainty in the development of the SBR system; and (4) the development of an integrated assessment model (IAM) framework, which will allow current and future trends in environmental change and policy decisions to be explored across a broad range of biophysical and socio-economic processes. Section 5 discusses the benefits, the difficulties, and further developments of the model framework.

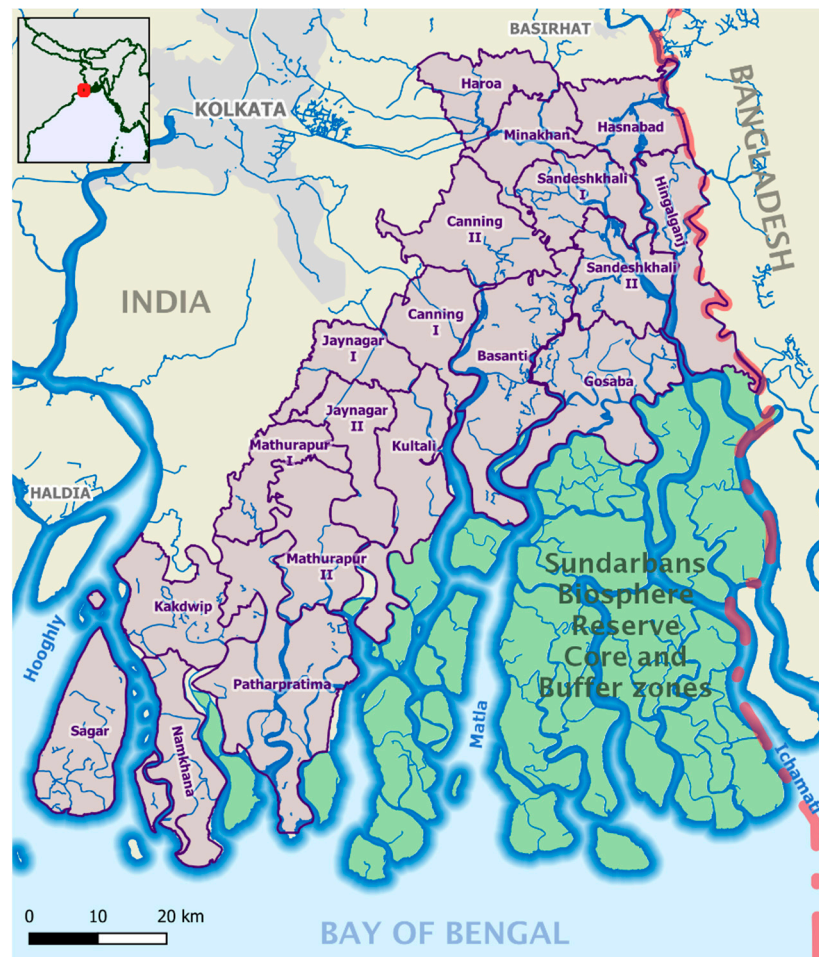
## 2. Study Area: The Sundarban Biosphere Reserve

The Sundarban Biosphere Reserve (SBR, 1989) (21°32' N–22°40' N and 88°05' N–89° 51' E) of India comprises an area of 9630 km<sup>2</sup> and is located in the tidally active western lower deltaic plain of the GBM delta, the second largest and most populous delta in the world [21]. The SBR is demarcated by the Ichamati-Kalindi-Raimongal rivers on the east, the Hugli river to the west, the Bay of Bengal in the south, and 'Dampier Hodges line' (the limit of the tidal river network and extent of erstwhile mangrove forest in 1830) to the north (Figure 1). The region is tropical, monsoonal, and experiences cyclones with extensive low-lying floodplains with elevations up to 6 meters above sea level. Tides and extreme water levels during storms and cyclones can result in sea water travelling 50–100 km inland from the coastline [22]. The extensive interconnected tidal channels create over 100 islands in the SBR, many of which have been deforested and embanked since 1800.

Administratively, the SBR comprises 19 blocks forming the entire South 24 Parganas district and the southern part of the North 24 Parganas district in the state of West Bengal. The population is 4.4 million (Census, 2011) and growing rapidly at an estimated and spatially varied rate of 14.9% [23]. Many live within rural settlements, relying heavily on natural resources for their livelihoods. Approximately 34% of the population live under acute poverty [24] and lack basic human requirements of water, health, and sanitation. Within the SBR, livelihoods are varied and multi-dimensional. The exposure of the region to frequent natural hazards has seen the majority of the population adapt to multiple livelihood activities throughout the year [24]. However, agriculture is the dominant livelihood [25] with nearly 60% of the total working population depending upon it as their primary occupation, either as cultivators or agricultural laborers [26]. In addition to agriculture, the extensive tidal creeks and inland natural wetlands create major livelihood opportunities in fishing (riverine, tidal-brackish water, marine) and aquaculture (freshwater or brackish) [26].

Alongside the growing populace, the SBR contains 40% (or 4200 km<sup>2</sup>) of the world's largest contiguous mangrove forest (often referred to as the Sundarbans), which continues across the border into Bangladesh. Over the last two centuries there has been significant encroachment on these mangroves, but they are now protected, being designated a UNESCO World Heritage (1987) and Ramsar Site (2019). They comprise 46 islands with exceptional biodiversity, including 90+ endangered species and the iconic Royal Bengal tigers. The mangroves provide an important spawning ground and nursery for numerous economically important species of fish and crustaceans [27], serve as a natural barrier to protect against cyclones and storm surge, and play a significant role in coastal carbon sequestration [28]. A sizable proportion of SBR residents depend on the mangroves for their livelihoods [29]. In particular, tribal communities living in the fringes of the mangrove collect Non-Timber Forest Products like honey, tannins, medicinal plants, small fishes,

and crabs [30]. These products can make a significant contribution to household annual income [31]. The mangrove also supports other livelihood activities such as the collection of prawn seeds for aquaculture [32].



**Figure 1.** Sundarban Biosphere Reserve (SBR), West Bengal, India. The 19 blocks of the SBR Transition Zone, which comprise the populated study area, are shown in purple. The protected mangrove forest is shown in green.

Like all delta regions, the SBR system is experiencing multiple pressures from global, regional, and local drivers, including those related to climate change, rising sea levels and subsidence, coastal erosion, lack of freshwater and sediment supply, and a growing population and changing land use [21,33]. The region is especially vulnerable to cyclone landfall and storm surges that threaten life, infrastructure (embankments, houses, roads, etc.), and mangrove habitat. Cyclone Sidr, in 2007, severely affected a significant proportion of the Sundarban mangrove forest across Bangladesh and India with recovery estimated at 10 to 15 years [34]. Cyclone Aila (2009) caused further damage to the mangroves and damaged more than 500 embankments and 900,000 homes with winds of up to 120 km/hr [35]. More recently, it is estimated that around 200,000 farmers were severely affected by sea water intrusion and pluvial flooding caused by cyclone Amphan in 2020 [36]. The frequency of severe cyclonic storms in the Bay of Bengal increased by >20% over the period 1877–2005 [37].

The northern Bay of Bengal has experienced relative sea level rise of the order of 8 mm/year in the last three decades [38]. This rate is considerably higher than the global mean (3.3 mm/year). Relative sea-level rise is about 5 mm/year at Diamond Harbour tide gauge over 50 years, reflecting a regional subsidence across the delta [39]. This has con-



tributed to severe coastal erosion and several islands in the SBR (Lohachara, Suparibhanga, and Bedford) have been completely lost [40]. The total loss of mangrove area due to coastal erosion alone was found to be 107 km<sup>2</sup> between the years 1975 and 2013 [41]. Land loss is driving migration of people from several vulnerable inhabited areas, primarily in the southwest of the SBR [42].

The wider GBM delta dynamics are considerably affected by direct human intervention in the form of the Farakka Barrage, which diverts water from the Ganga into the otherwise moribund Hugli River toward Kolkata. However, despite the increased upstream flow into the Hugli, little freshwater travels into the SBR and there are acute shortages in the dry season. Most of the rivers flowing through the SBR have lost the connection with their sources due to various natural and anthropogenic reasons, and their estuarine character is now maintained by the monsoonal runoff alone [43–45]. This lack of freshwater combined with the rise in sea level is thought to be contributing to the deterioration of the health of the mangrove forest [46] via increasing salinity. Salinization has significant adverse effects on the Sundarbans' mangrove forest: Increased salinity and anoxicity inhibit nutrient cycling and encourage nutrient-poor soil [47], damaging the Sundari trees, slowing forest growth, and reducing productivity and biodiversity [48]. The accumulation of salts in soils and freshwater driven by both natural (e.g., tidal inundation) and anthropogenic (e.g., excessive groundwater extraction) processes is a growing concern in the region. Salinization has direct implications, not only for natural ecosystems and habitats, but also for food and water security, livelihoods, and health [49]. Saltwater intrusion into groundwater often takes place within the shallow aquifers due to influent discharge of the rivers [50], affecting freshwater supply in the dry season for drinking and agriculture.

It is estimated that 75% of land within the inhabited areas of the Sundarbans is used for agriculture, mainly mono-cropped, rain-fed Aman rice cultivation in the wet (kharif) season [51]. The timing and amount of monsoon rainfall are critical to the successful production of the rice crop due to the scarcity of freshwater [52]. However, variability in monsoon intensity and timing is common in the SBR [53], which can have significant impacts for the SBRs' inhabitants. Moreover, further changes to the seasonal climate in the region have been predicted in the coming decades, including an extended dry season [54–56]. The shallow groundwater, often brackish, is not suitable for drinking [27,57] or for agricultural irrigation. Therefore, dry (rabi/boro) season crop cultivation is limited and most agricultural land lies fallow [58]. In the Sundarbans' blocks of the North 24 Parganas, up to 40% of the cropped area is thought to be affected by salinity [27].

The rural population is highly dependent on fisheries both for nutrition and livelihood generation. Approximately 124,000 people work full time in fishing and allied activities [59] within the SBR. Fisheries as a sector represent 4.1% of the Gross Domestic Product (GDP) of the Indian Bengal Delta (IBD) [60]. Recent decades (from 2002/03 to 2017/18) have seen a substantial increase in the number of mechanized (from 1000 to 5400) and non-mechanized (from 250 to 3200) boats operating in the coastal water of the Bay of Bengal [61]. However, despite the increased fishing effort, the total annual marine fish catch for this region has seen only a limited increase [61]. Moreover, several fish species show decreasing catch trends over the last decade. They include some important commercial fish species like hilsa (*Tenualosa ilisha*; Hamilton, 1822), as well as some fish species forming the bulk of the total marine catch, like ribbonfish (*Trichiurus lepturus*; Linnaeus, 1758) and Bombay duck (*Harpodon nehereus*; Hamilton, 1822). The hilsa fishery in West Bengal has been overexploited, with fishing pressure on the hilsa stock exceeding the maximum sustainable yield limits [62]. Furthermore, the impact of climate change and management policies on the productivity of the Bengal Delta is projected to decrease marine fisheries' productivity [63]. The low-income rural population of the SBR is highly dependent on the low-cost fish species (e.g., ribbonfish, Bombay duck, anchovy, Indian mackerel, etc.) as a source of animal protein for nutrition uptake. Thus, unavailability of these fish species impacts them the most [64].

Land-use/land-cover change is changing in the SBR due to natural and human influences [65]. The expanding megacity of Kolkata (about 15 million people in 2020), while

not in the SBR, is located within approximately 50 km of the northern SBR. The direct and indirect influence of Kolkata on the SBR appears to be growing as the city expands [23] and, if the city continues to expand as projected, this will potentially lead to increased population and urban development pressure within the SBR. A recent notable land-use change in the SBR is the rapid expansion of brackish water aquaculture. Total aquaculture area of Sundarbans in 2017 was estimated to be 51,913 ha [66]. This is estimated to be growing at a rate of 2% per annum, 98% of which is from the conversion of agricultural land [65]. Aquaculture has become an important livelihood option for many within the Sundarbans due to relatively easy access to the saltwater and availability of naturally grown seeds of various shrimps and fishes. The majority of the aquaculture farmers practice traditional farming methods, where, unlike more sophisticated semi-intensive practices, ponds are stocked with polyculture species collected from the wild (rivers, creeks), rather than monocultures from hatcheries. Ponds are often naturally stocked during high tide through sluice gates and the use of supplemented feed, fertilizers, disinfectants, fungicides, antibiotics, and probiotics are uncommon. However, in recent decades there has been remarkable growth in the sector [26,65,67], driven by the introduction of sophisticated culture techniques, growing market demand, private investment, and change in the Government's policies during the 1990s, which promoted aquaculture development in India and led to huge commercial input in the industry [68].

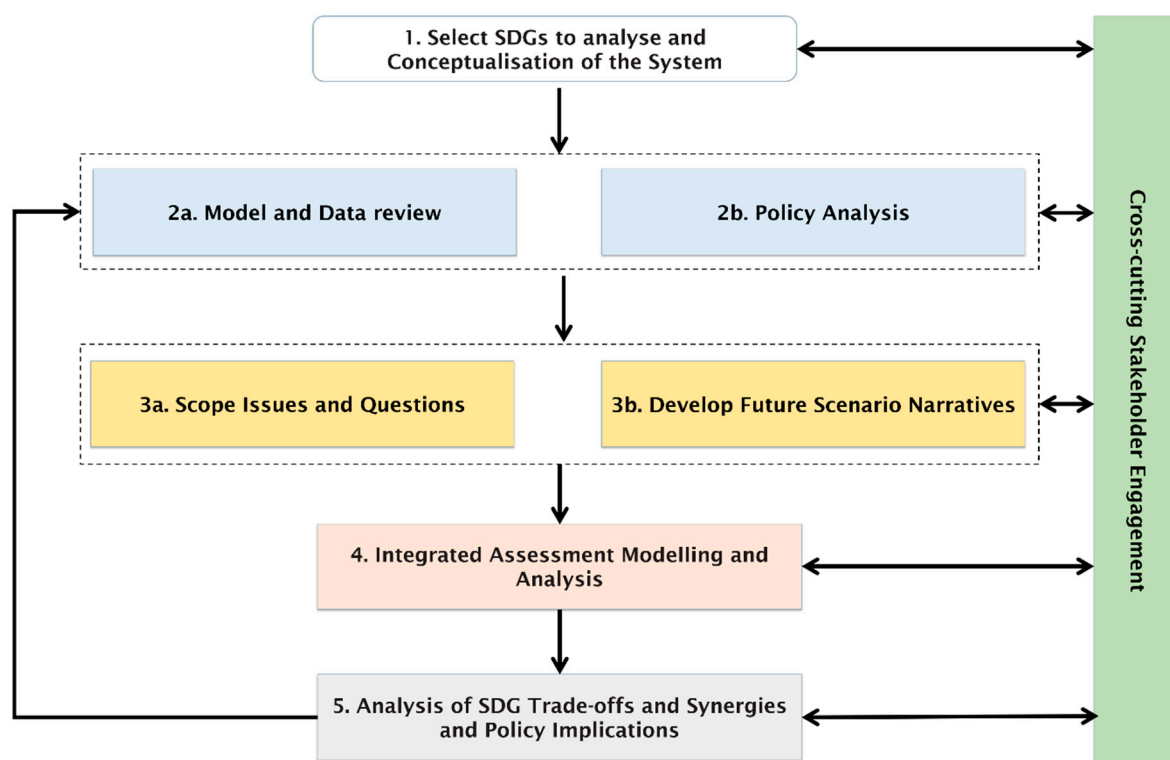
### 3. Participatory Integrated Assessment Approach

This study builds upon earlier deltaic research and analyzes the trade-offs and choices raised by six (of the 17) SDGs within the SBR across a range of development trajectories. To achieve this research goal requires a system perspective, especially concerning the social, physical, and ecological delta components and their interactions. The conceptual approach that we follow to gain system-specific knowledge of these dynamics and their interlinkages for the purpose of assessing current and future interactions related to specific SDGs is summarized in Figure 2. The approach consists of five steps including the generation of scenarios of future socio-economic and environmental conditions along with determining interesting, plausible, and distinct strategies for targeting the SDGs' achievement. Stakeholder engagement occurs throughout the process, reflecting the participatory nature of the assessment.

The first stage of the approach (Step 1) is the conceptualization of the system and the selection of the SDGs to analyze, influenced by stakeholder and research interests. Step 2 provides a review of the models, knowledge, and data available for the study region alongside an analysis of current government policies (at national or regional/state level). The model and data review allows assessment of which processes can be accurately represented through current models and data. While the policy analysis allows the identification of key issues relevant to the strategic SDGs and how these issues are being addressed by national and regional governments, it also provides information on likely future trends, as these can be defined by policy targets. The focus of stakeholder engagement throughout Step 2 provides information on key issues and drivers of change within the study area and allows validation and addition of information to policy evaluation outputs to ensure local issues are being properly represented. The frequent dialog and formation of relationships with government and policy makers allowed by the cross-cutting stakeholder engagement, which informs every step of the approach, ensures that researchers understand stakeholder-specific needs and interests and can identify how (i.e., the pathways by which) project outcomes can have 'real world' impact and influence and inform future policy discussions.

These initial activities feed into the development of key questions (Step 3a) based on important potential trade-offs between SDGs. Future scenarios of change (Step 3b) are developed based on the key issues and likely future trends identified by policy and stakeholders as well as our holistic understanding of the system and the data and models available to accurately represent its subcomponents. The questions are explored within each scenario using an integrated assessment modelling (IAM) approach, which brings

together models and data of both the human and environmental aspects of the system based on our current understanding and capabilities (Step 4). Outputs from the integrated assessment are evaluated in terms of SDG trade-offs and synergies (Step 5) and these results will be fed back to stakeholders, which in turn may influence policy. The whole approach is cyclical in nature, allowing for iterations in activities to occur with updated systems' knowledge and information, new applications of policy, or strategic questions of interest.



**Figure 2.** Steps of the integrated assessment approach used to gain system-specific knowledge of human–natural processes and their interlinkages for the purpose of assessing interactions in specific Sustainable Development Goals (SDGs).

#### 4. Developing an Integrated Assessment Tool for the SBR

This section describes in detail how Steps 1–4 of the participatory integrated assessment approach (Figure 2) were operationalized to develop a modelling framework that allows socio-ecological interactions related to the selected SDGs to be explored for the Sundarban Biosphere Reserve.

##### 4.1. Selection of SDGs to Analyze and Conceptualization of the System (Step 1)

The focus of this study is on SDG interactions within the deltaic system of the SBR, where rich and highly valued ecosystems are contrasted by the severe poverty of the human inhabitants [26]. Hence, we focused upon the mechanisms that link terrestrial and marine ecosystems and their service to socio-economic outcomes and selected to analyze SDG1 (No Poverty), SDG2 (Zero Hunger), SDG10 (Reduced Inequalities), SDG13 (Climate Action), SDG14 (Life Below Water), and SDG15 (Life on Land). Researchers worked with stakeholders to conceptualize the links between key processes and issues affecting sustainable development in the SBR (detailed in Section 4.4).

##### 4.2. Model and Data Review (Step 2a)

An extensive review of modelling capability and data available for analysis of the SBR was conducted and a catalog of what existed was created. This was used to indicate which aspects of the system could be accurately represented within our analysis and over what time periods (e.g., were future predictions available). The review collated

information (description, spatial and temporal resolution, source and availability) on data and models (process and statistical) from previous, relevant, large-scale research programs such as DECCMA and ESPA deltas [19,33,69] along with the wider literature and public data archives. Approximately 80 biophysical and socio-economic data sets and models were identified across 15 subcategories (e.g., Climate, Ocean, Hydrology, Economy, Infrastructure and Access, etc.). The review indicated strong availability of data and modelling methods to explore processes such as agriculture, mangrove extent, community level poverty, and land-use and land-cover change. However, data and/or methods for modelling processes such as migration, river salinity, and household level poverty were lacking, highlighting potential areas where additional data collection and/or model development would be required.

#### 4.3. Policy Analysis (Step 2b)

In parallel to the model and data review, an assessment of existing national and regional policy statements and goals was carried out. This sought to identify the development objectives within the SBR and the associated government targets and policies and the key strategic issues (e.g., poverty alleviation, rural economic growth) and the sustainability principles addressed. The policy analysis allowed the examination of policies that contribute to or hinder achievement of the selected SDGs, to identify issues perceived as important by the government, and develop understanding of their current and likely future trends in respect to existing policy implementation.

The review indicated that few national or regional policies and plans have long-term, specific targets (beyond 2030), although they may have long-term goals where policies may extend across multiple planning and strategy cycles. The majority of policies are developed at national levels under the line ministries and supported through central sector funds or central supported funds and implemented at state and local government level. Sectoral policy (in agriculture, development, fisheries and aquaculture, social protection, tourism, coastal zone management) directions were identified for the SDG themes chosen by the project. These policies indicate a series of potential interactions [2], including trade-offs and synergies relating to the SDG indicators and targets. Such interactions are mediated by a development deficit in the SBR and may be spatially explicit, with few livelihood alternatives, and often low policy implementation or enforcement (e.g., in land-use change restrictions within the coastal zone mandated under the Coastal Regulation Zone Notification [70] in some sectors). Potential trade-offs focused on development sectors (agriculture, aquaculture, water resources, infrastructure, and tourism) and the high environmental quality and conservation policies over much of the SBR (Table 1). Potential synergies were found in the development of policies for social protection measures (SDG1) and food security (SDG2) and development, support for community resilience (SDG1,2) and climate action (SDG13), and specific support to Scheduled Castes and Scheduled Tribes, women, and child welfare (SDG10).

As an example of the interactions provided by a specific policy, the Mahatma Ghandi National Rural Employment Guarantee Act (MGNREGA) national legislation from 2005 is targeting rural poverty through a guaranteed scheme for 100 days of waged employment. Implemented at State level, with actions coordinated at Panchayat (local government) level, the scheme contributes, as the 'core of the core', to achieving SDG 1 No Poverty. However, a more inclusive mapping of MGNREGA schemes to SDGs [71] highlights the contribution to SDG 5 Gender Equality, SDG 8 Decent Work and Economic Growth, and SDG 10 Reduced Inequalities. The anticipated trade-off between policies and SDG is the social protection measures through MGREGS and the potential of perverse incentives that may trap people in poverty [26].



**Table 1.** Trade-offs (–ve interactions) and synergies (+ve interactions) between policies and SDG targets in the SBR.

SBR Policy Trade-Offs	SDG Trade-Offs	SBR Policy Synergies	SDG Synergies
Economic development (coastal economic zones within SBR and urbanization)	SDG1, SDG11 Rural poverty alleviation, land reforms to support small scale ownership vs. intensification and urbanization	Encouraging small and marginal farmers including Scheduled Castes and Scheduled Tribes & women.	SDG1, SDG2 and SDG10 Actions for support to agriculture and poverty targeted at most marginalized
Social protection measures addressing poverty and economic development	SDG1, SDG11, SDG8 Rural poverty alleviation through social protection vs. economic development	Promoting the concept of zero tillage/minimum tillage in vulnerable areas, and sustainable water withdrawals	SDG2, SDG15, SDG 13, SDG6 Climate smart agriculture promotion and water management
Impacts of rural agricultural Intensification and mechanization of agriculture, water requirements and environmental flows	SDG2, SDG6, SDG14 Agricultural intensification through irrigations vs. environmental flows and groundwater availability	Regulation of fisheries catch and sustainable aquaculture and food and nutritional security	SDG 14, SDG2 Sustainability fisheries and food and nutritional security
Irrigation policies for agricultural intensification vs. drip irrigation for climate resilience	SDG2, SDG13 Agricultural intensification for export vs. drip and rainwater harvesting for climate action	Social protection measures and mangrove conservation and rehabilitation, shoreline protection	SDG1, SDG15 Support to waged employment funding activities to support mangrove regeneration
Conversion of agricultural land to aquaculture (consequent change in labor equality and livelihood impacts)	SDG1, SDG2, SDG10, SDG14 Poverty alleviation vs. change to employment and migration in aquaculture	Sustainable tourism and infrastructure developments	SDG1, SDG2, SDG6, SDG8 Infrastructure development that supports both tourism and connectivity (markets/water, sanitation)
Sustainable tourism growth and biological conservation	SDG1, SDG15, SDG13, SDG14 Growth in tourism facilities vs. conservation of coastal zone and mangroves	Embanking and coastal defense and land-use change	SDG1, SDG15 Embanking supports land-use alternatives, and land consolidation
Embanking protection and subsidence/flood levels	SDG1 SDG15 Poverty alleviation vs. and natural resource management	Community resilience and Climate change actions	SDG1, SDG13 Support for poverty alleviation and climate change actions

#### 4.4. Stakeholder Engagement

Engagement with secondary and tertiary expert stakeholders, including government, non-governmental Organizations (NGOs), and local academics, fed into selection of the SDGs and the conceptualization of the SBR system by providing expert knowledge on the regional-specific links between human and natural processes. The regular iterations with stakeholders throughout the integrated assessment approach supports a co-productive process in which stakeholder perspectives inform project scope, scenario development, and the implications and interpretation of results. The methodological approach reflects Allan et al. [72], with a process to identify stakeholder perspectives on key issues, drawing on these to create scenarios, and then evaluating the likely response of these issues to scenarios of change based on modelling and expert opinion of stakeholders.

Semi-structured interviews to explore the key processes and drivers affecting food, poverty, and inequality in the SBR, alongside key policy narratives and controversies, were held with two recognized experts. These were a former director and current member of the Sundarbans' development board, as well as the former head of the Climate Adaptation program of WWF (World Wide Fund for Nature), and an independent NGO director with over 15 years of experience working within the SBR holding an interdisciplinary PhD on livelihoods, governance, and environmental change in SBR. These interviews, along with a review of relevant literature, led to an initial list of key issues, processes, and linkages

to the SDGs. A two-day workshop with representatives from government departments (including Sundarbans Affairs) and NGOs working on biodiversity conservation and health in SBR broadened the stakeholder input to our system conceptualization within the delta. Following diverse presentations from the participants on the current state and issues in the SBR, five mixed, breakout groups independently created simple causal diagrams to identify important drivers, their effects, and secondary effects, in response to the question “What are the key drivers that will affect sustainable development in the SBR area?”. They were asked to focus on the next 10 years and include positive and negative drivers and effects. The interviews, reviews, and workshop breakouts were analyzed to generate a list of 129 unique causal relationships, after different phrasings of similar concepts were combined. The frequency of mentions was counted for variables on the causing side of each relationship to evaluate the most salient driving processes according to these stakeholders (Figure 3).



**Figure 3.** Word cloud of the frequency of mention of variables that were reported to influence another variable in workshop causal diagrams and expert interviews. “Land ho” refers to land holdings.




To operationalize this list of variables and inform the development of the integrated assessment modelling (Figure 2, step 4), results from the stakeholder analysis were combined with those of the model and data review and variables were assigned to three categories: (1) those that could be explicitly modelled, (2) those that could not be modelled, or (3) those required as model inputs and thus needed to be represented in scenarios. In a second stakeholder workshop, participants' opinions were elicited on how these variables would change into the future. Four breakout groups independently discussed and scored how each of the identified group of driver variables would change going forward to 2050 [68] (using a semi-quantitative scale from  $-3$ : very large decrease, to  $+3$ : very large increase) (Table S1). Rapporteurs were also used to record qualitative notes on why stakeholders believed such trends would emerge and key uncertainties and geographical differences in expected trends (which were sketched on maps). The outcome from this secondary stakeholder engagement gave a strong rationale to focus on the impacts surrounding land use and land-use change, particularly the loss of agricultural land to erosion, aquaculture, and urbanization.

#### 4.5. Defining Key Questions of Interest (Step 3a)

The research team combined outcomes from the initial policy analysis and stakeholder engagement with those from the model and data review to identify several high-level issues where there was: (1) likely trade-offs or synergies in policy areas; (2) a keen interest by stakeholders for improved understanding; and (3) the modelling capability and data availability to allow for robust exploration of the issue. Table 2 summarizes the issues

identified and their connection to the selected SDGs, current policy, and available methods and data for analysis.

**Table 2.** Summary of key issues to explore within the SBR, their links to SDGs and current policy, and overview of the type of methods and data available for analysis.

Areas for Exploration	SDGs Considered	Links to Policy Initiatives	Overview of Methods and Data Available
Increased provision of freshwater		Soils health <sup>1,2</sup> , increase efficiency of irrigation <sup>3</sup> , encourage diversification of high value crops <sup>4</sup> , doubling farmers incomes <sup>2,5</sup> , rainwater harvesting <sup>2,6</sup>	Agricultural modeling, mangrove health indicators, Statistical poverty modelling, socio-economic data, livelihood information.
Aquaculture expansion		Control of land-use change <sup>7</sup> , support for sustainable agriculture <sup>8,9</sup> , regulate growth of inland aquaculture, diversification of species in freshwater aquaculture <sup>10</sup> , triple export from fisheries and aquaculture sector <sup>11,12</sup> , double income of fishers and fish-farmers <sup>7</sup>	Land-use/land-cover modelling, agricultural modelling, aquaculture sector knowledge and trends, statistical poverty modelling, livelihood information.
Mangrove trends, including realignment/retreat		Rehabilitation and regeneration of mangroves <sup>13</sup> , riverbank afforestation <sup>14</sup> , sustainable management, ecotourism <sup>15</sup> , coastal resilience <sup>2</sup>	Mangrove extent modelling, mangrove health indicators, land-use/land-cover modelling, fisheries sector knowledge and modelling.

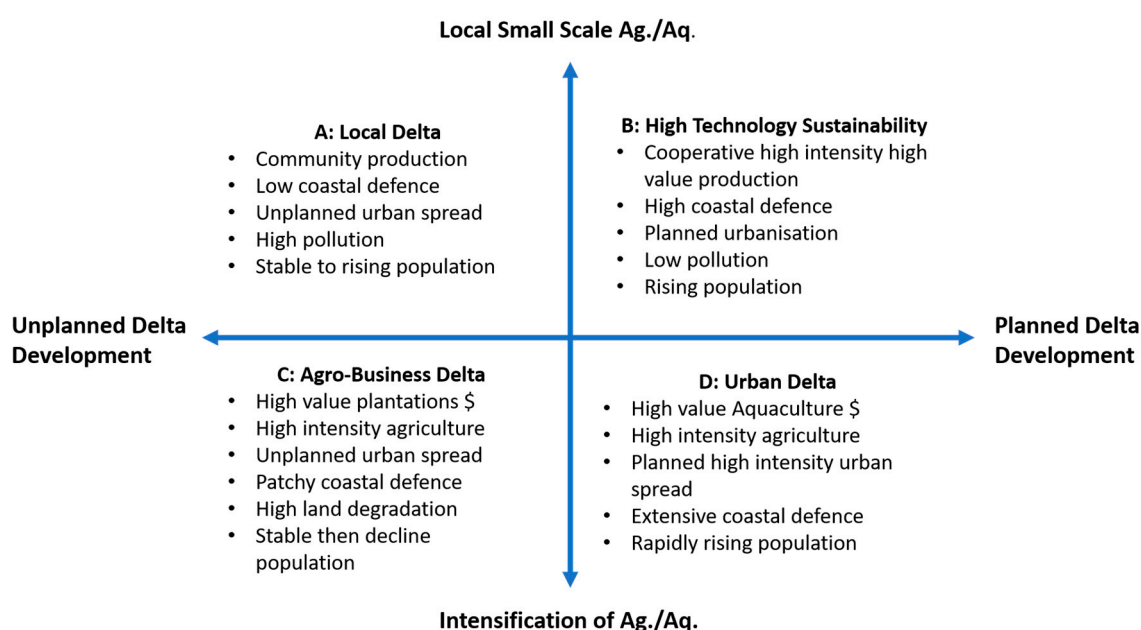
<sup>1</sup> Singh, J. and Negi, A. (2020) Soil Health card: An overview. Chapter 4: Ed. Kumar, N. Current research in soil science, Aiknik Publication. <https://doi.org/10.22271/ed.book.743>; <sup>2</sup> National Food Security Mission; <sup>3</sup> Pradhan Mantri Krishi Sinchai Yojana (Prime Minister's Irrigation Scheme); <sup>4</sup> Chand, R. (2017) Doubling Farmers' Incomes NITI Aayog Policy Paper No 1/2017 Available online: [http://niti.gov.in/writeraddata/files/document\\_publication/DOUBLING%20FARMERS%20INCOME.pdf](http://niti.gov.in/writeraddata/files/document_publication/DOUBLING%20FARMERS%20INCOME.pdf) (accessed on 24 January 2021); <sup>5</sup> ICAR (2016) State Specific Strategies for Doubling Farmers Income – Indian Council of Agricultural Research Available online: <https://icar.org.in/sites/default/files/Doubling-of-Farmers-Income-02.pdf> (accessed on 24 January 2021). 2022; <sup>6</sup> National Mission for Sustainable Agriculture (NMSA) Rainfed Area Development component; <sup>7</sup> GoI (2019) COASTAL REGULATION ZONE NOTIFICATION MINISTRY OF ENVIRONMENT AND FORESTS [https://www.iczmpwb.org/main/pdf/czm\\_laws/CRZ%20Notification%202011.pdf](https://www.iczmpwb.org/main/pdf/czm_laws/CRZ%20Notification%202011.pdf) regulations under the Environment (Protection) Act, 1986; <sup>8</sup> GoI (2020) draft National Fisheries Policy 2020 Available online: [http://nfdb.gov.in/PDF/National\\_Fisheries\\_Policy\\_2020.pdf](http://nfdb.gov.in/PDF/National_Fisheries_Policy_2020.pdf) (accessed on 24 January 2021); <sup>9</sup> GoI (2019a) draft of National Mariculture Policy 2019 Available online: [http://nfdb.gov.in/PDF/Revised\\_draft-0NMP-2019.pdf](http://nfdb.gov.in/PDF/Revised_draft-0NMP-2019.pdf) (accessed on 24 January 2021); <sup>10</sup> (GoI 2019b) National Inland Fisheries and Aquaculture Policy: Draft Available online: <http://nfdb.gov.in/PDF> (accessed on 24 January 2021) GoI (2020) draft National Fisheries Policy 2020; <sup>11</sup> MINISTRY OF AGRICULTURE AND FARMERS WELFARE (Department of Animal Husbandry, Dairying and Fisheries) (2017) National Policy on Marine Fisheries, 2017 Accessed:24/-1/2-21; <sup>12</sup> Neel Kranti - Mission (Blue Revolution); <sup>13</sup> Green India Mission, National Strategy and Action Plan for mangroves; <sup>14</sup> National Afforestation Programme (NAP); <sup>15</sup> Government of West Bengal (2019) West Bengal Tourism Policy Available online: [https://www.wbtourismgov.in/home/download/pdf/west\\_bengal\\_tourism\\_policy\\_2019.pdf](https://www.wbtourismgov.in/home/download/pdf/west_bengal_tourism_policy_2019.pdf) (accessed on 24 January 2021).

#### 4.6. Future Scenario Narratives (Step 3b)

Scenario analysis is a common tool for assessing uncertain but plausible future development in complex systems. A scenario of future conditions is a complete set of external parameters defining the boundary conditions in which the system operates [73]. To constrain the degrees of freedom within scenarios, one method is to focus on a limited number of scenarios based on contrasting extremes. These extremes provide insight into the end member states and possibilities for the future and, in doing so, offer potential conditions of the states that could exist between these boundaries [19,74,75]. The intention here is that by identifying the extremes, as stipulated by the stakeholders and moderated by the partner expertise, it is possible to create a plausible space for assessment of scenarios. However, the point of the scenarios is not to predict the future but explore plausible future directions to assist in the integrated assessment analysis of future trends in socio-economic and environmental change. In this work, a simple, four-state scenario matrix is adopted. The matrix is based on two axes that presented key policy choices and/or broad directions of travel that are important to the management strategy for the delta over the coming decades [76]. Here, a focus on land-use decisions was taken, as this was a significant issue

raised by the stakeholders that lies at the center of trade-offs between SDGs, especially with the pressure of the growing population in the SBR and the expanding neighboring megacity of Kolkata. The choices along the two axes of the scenario quadratic were the continuum between large-scale agricultural and aquaculture intensification and localized agricultural and aquaculture production on the vertical axis and the degree to which delta urban development is planned or unplanned on the horizontal axis.

In this approach, it was possible to identify four, broad, future scenarios for the SBR bounded by extremes (Figure 4). These are (1) Local Delta, (2) High technology sustainability Delta, (3) Agro-Business Delta, and (4) Urban Delta. Key features for each scenario narrative are shown in Figure 4. Further stakeholder engagement was sought, via an online workshop, to refine scenario narratives and identify stakeholder perspectives around likely and preferred pathways and corresponding possible trade-offs and synergies between SDGs.



**Figure 4.** Four future scenarios for the SBR region aligned against axes of uncertainty surrounding the intensity of agriculture and aquaculture production and the degree to which delta development is planned or unplanned. A full description of each narrative is given in supplementary information.

#### 4.7. Developing an Integrated Model Framework (Step 4)

Coupled natural-human systems, such as the SBR, are complex and dynamic, integrating phenomena across multiple scales of space and time. To model the complexities related to sustainable development challenges in these systems, a flexible framework is needed that allows integration of knowledge across environmental and socio-economic disciplines [77]. To successfully capture such wide-ranging and cross-sectoral knowledge within a single framework requires integration of different types of quantitative models (e.g., mechanistic, statistical, probabilistic) alongside qualitative and participatory information (e.g., expert opinion and narrative analysis). In this section, we set out a suitable integrated framework for the SBR.

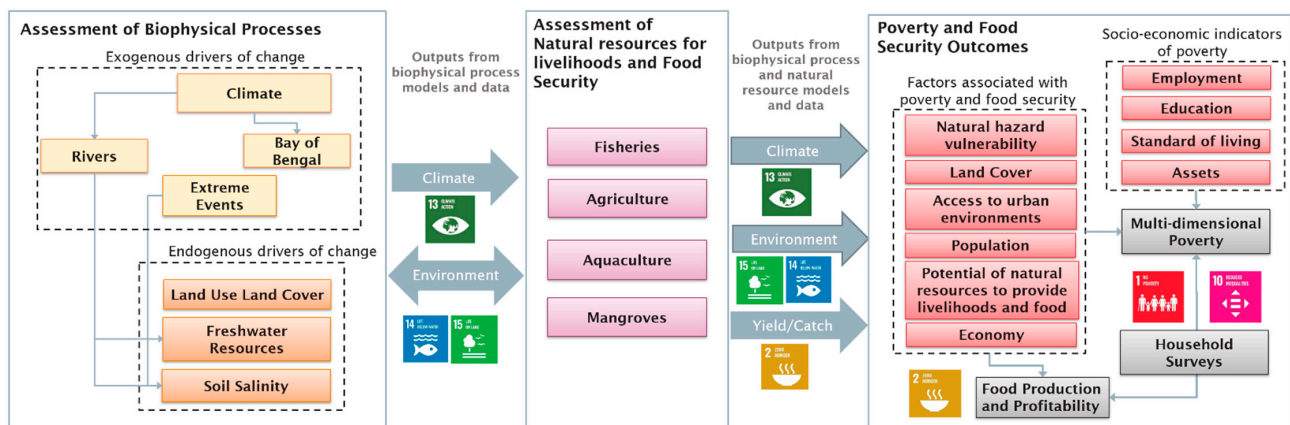
Integrated Assessment Models (IAMs) are tools that are often deployed to help assess how human development and societal choices affect the environment and each other. By combining knowledge across disciplines, they can help model real-world problems of interest to decision makers [78]. IAM frameworks and tools are developing rapidly and are increasingly being used to support policy processes [79,80]. They can take many forms and can have a wide and varied range of objectives, methods, and spatial and temporal dimensions with examples including acid rain [81,82], air quality [83], climate change risks (e.g., [84,85]), biodiversity and ecosystem risks (e.g., [86]), infrastructure provision [87],



and development choices in deltas [19,88]. Hence, IAMs can be beneficial for exploring the behaviors and evolution of complex, coupled, human–natural systems under a range of future scenarios and policy choices, allowing potential trade-offs and consequences to be identified across a broad range of thematic components. When used in conjunction with stakeholder participation, IAMs are able to encourage dialogue and innovative problem solving [7]. Using such integrated modelling approaches to assess the delivery of SDG targets has several potential benefits; primarily, it may prevent incoherent policy making where a strategy for meeting one target undermines achieving another target. However, few studies have applied IAMs to examine SDG interactions, especially on a subnational scale.

A recent assessment by van Soest et al. [89] examined how IAMs could be repurposed for the analysis of SDGs to inform integrated policy. They found that, although many existing IAMs cover SDGs related to climate and resource use, other dimensions of the 2030 agenda, such as equality or human development issues, were poorly represented. Collste et al. [90] introduce the integrated Sustainable Development Goal (iSDG) IAM model to simulate feedbacks among and within a country's environment, society, economy, and governance sectors. The iSDG allows for development scenarios to be generated and the impacts of potential policy interventions on progress toward achieving the SDGs to be examined, but only at the national level [90,91]. At a subnational level, the fully integrated Delta Dynamic Integrated Emulator Model ( $\Delta$ DIEM) was developed to examine trade-offs and trends between natural and socio-economic processes related to ecosystem services under a range of future climate and development scenarios for coastal Bangladesh [13,92]. Hutton et al. [7] demonstrated how this specific, regional IAM could potentially be used to investigate SDG trade-offs within a delta environment. They examined interactions between SDG 2 Zero Hunger and SDG 8 Decent Work and Economic Growth, by examining how progressive farming methods may increase food security, tackle chronic hunger, and potentially increase livelihood outputs when compared to more traditional farming practices, which were assumed to be less environmentally damaging.

To investigate the trade-offs and interactions between SDGs within the complex deltaic socio-ecological system of the SBR, our IAM framework is both multisectoral, incorporating both human and natural processes, and allows for mechanisms to implement policy choices of interest to stakeholders. It is informed by  $\Delta$ DIEM [92] but the framework here has been redesigned to account for operational limitations, building on existing capabilities and ensuring that it can be implemented within the available resources. It aims to provide outputs that are both policy- and stakeholder-relevant and, additionally, that can be linked to a broad range of subthematic SDG target indicators such as those related to key socio-environmental and biophysical drivers and the associations between water resources, agriculture, aquaculture, fisheries' production, and multidimensional poverty. The framework allows outputs to be simulated forward to the end of the SDG agenda in 2030 and beyond, to 2050 and even longer if appropriate (e.g., mangrove response to sea-level rise). However, there is more uncertainty concerning socio-economic relationships and scenarios beyond 30 years. A schematic of the framework is shown in Figure 5. This schematic indicates where there are interactions between individual biophysical and socio-economic processes of interest and where outputs can be linked to thematic SDG indicators. The proposed framework is divided into three sectors, modelling and assessment of (1) biophysical processes, (2) natural resources for livelihood activities, and (3) poverty and food security outcomes. The biophysical processes are further divided into two categories. These are (1) exogenous factors representing those drivers of change that act on global or regional scales and (2) endogenous factors representing drivers of change that occur on a local level within the SBR. Natural resources for livelihood activities represent natural resources important for livelihood practices that make up a significant proportion of occupations and income generation for the local population. A description of each of the individual biophysical and socio-economic framework components and the submodels and data sources currently available to the IAM is given in Table 3.



**Figure 5.** Proposed IAM framework for the integrated assessment of the interactions and trade-offs of selected Sustainable Development Goals within the Sundarban Biosphere Reserve. Boxes represent subcomponents where models and/or data are available for analysis. Arrows indicate information flow between subcomponents. Colors are used to group subcomponents and aid visualization. Yellow = factors acting as exogenous drivers of change, orange = factors acting as endogenous drivers of change, purple = models of natural resources linked to livelihoods, gray = socio-economic analysis, pink = factors feeding into socio-economic analysis coming from other subcomponent analysis, scenarios, and data.

Integration of the different models and data components that constitute the framework presented in Figure 5 is required if we are to gain insight into the complex interdependencies and relationships within the SBR system. However, integrating models, data, and knowledge from different disciplines with varying scales of analysis and analytical methods as well as differing computational needs can be challenging. Here we take a soft coupling approach to the integration of different model components, whereby in an iterative manner, the output of one component forms the input to another(s). This has several advantages compared to fully coupling submodel components into a singular integrated model that are often difficult to comprehensively validate due to their scale and complexity. Soft coupling of model components allows greater transparency, explicit understanding, and consideration of internal feedback connections between models and the flexibility to continually improve and update individual components [87]. Furthermore, linking the input and outputs of separate models in this way limits the possibility of locking in or out possible surprising system behaviors [93]. As indicated by Howells et al. [94], relying on previously established modelling methods is both time- and cost-effective and makes it easier to bring together experts from different disciplines. It also allows better use of existing knowledge and experience, something that is of particular importance in this study as we seek to maximize the wealth of data and knowledge gained through past research programs conducted in the region [19,33,69].

The framework allows for feedbacks between natural resource and biophysical sub-components (e.g., knowledge from analysis related to trends in aquaculture and agriculture are fed back into the land-use and land-cover modelling). However, it is recognized that the soft coupling integration method and the use of existing modelled outputs limits the potential for feedbacks, notably between the socio-economic analysis and the environmental modelling. Lack of feedback in this area is a common problem facing IAMs that attempt to link human–environment processes in general [89] and can be challenging to overcome because our understanding of them often involves ‘weak knowledge’ that does not translate well into formal equations that can be coded into biophysical and environmental models [95]. The integration method used here leaves a legacy for further development of the modules themselves, the addition of new features, and the development of hard coupled models like  $\Delta$ DIEM if these are thought to be useful.

**Table 3.** Description of IAM framework subcomponents. References are given for data and/or model output where applicable. Where modeling and primary data collection is being completed within the scope of the project, this is indicated as ‘project analysis’ and ‘Primary data’, respectively.

IAM Framework Sector	Sub Component	Purpose	Model/Data Description	Data Source/Reference
Biophysical Processes	Climate	Simulation of historic and future climate variability and change within the SBR	HadRM3P-Regional downscaled 25 km climate data for Representative Concentration Pathway (RCP) 8.5 between 1971–2099.	[96]
			Historical and future climate projections up to the year 2100 obtained for RCP 4.5 and RCP 8.5 from the Coordinated Regional Climate Downscaling Experiment (CORDEX), checked against observations and bias corrected.	[97]
Biophysical Processes	Extreme events	Identification of vulnerability to extreme events and natural hazards (cyclones and erosion)	Inundation layer based on Landsat-TM data (26 May 2009) after the severe cyclone Aila. Cyclonic wind hazard modelled using the Tropical cyclone risk model (TCRM). Erosion layers based on time series analysis of Landsat data.	[36]
Biophysical Processes	Major Rivers	Examine variability and changes in flow rates of the Hugli river	Integrated Catchment Model (INCA)-Simulations of river flow and water quality to 2050s and 2090s forced by downscaled HadRM3P climate data.	[98]
Biophysical Processes	Bay of Bengal	Examine rate of sea level rise in the Bay of Bengal	Global Coastal-Ocean Modelling System (GCOMS) 0.1 degree resolution projections of Sea Level Rise from 1970–2098.	[75]
			Create relative sea-level scenarios consistent with Intergovernmental Panel on Climate Change (IPCC) reports, including using Brown and Nicholls (2015) for subsidence	[99]
Biophysical Processes	Land Use/Land Cover	Explore current and future patterns in land use and land cover (LULC).	Landsat 30 m resolution satellite imagery 2001, 2011 and 2019	Project analysis
			A hybrid CA-Markov model to project LULC data till 2030 and 2050 based on classified LULC map of earlier time periods viz. 2001, 2011 and 2019. Similar to DasGupta [65]	Project analysis

Table 3. Cont.

IAM Framework Sector	Sub Component	Purpose	Model/Data Description	Data Source/Reference
Biophysical Processes	Freshwater resources	Examine variations and change in local river and estuarine salinity within the SBR and allow exploration of increased freshwater supply	MIKE 11 and MIKE 21 hydraulic model – One and two dimensional modelling of river salinity, water surface elevation, current speed, current direction, U and V velocity, etc.	Project analysis, primary data + unpublished data.
Biophysical Processes	Soil salinity	Determine the concentration and spatial variation of soil salinity.	Compilation of historic soil salinity measures combined with new <i>in situ</i> data.	[100–102]+ Primary Data
Natural Resources for livelihoods and food security	Fisheries	Understand the nature and dependency on small scale fisheries within the SBR.	Telephone surveys to gather information fishing systems, catch and issues facing small scale fishers in the SBR.	[103,104] + Primary data
		Determine future changes in fisheries within the Bay of Bengal	The Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS) and the European Regional Seas Ecosystem Model (ERSEM) combined with a Dynamic Bioclimate Envelope Model to simulate the distribution pattern and abundance of six selected marine fish species for three distinct fishing scenarios within the Bay of Bengal.	[63]
Natural Resources for livelihoods and food security	Agriculture	To estimate potential crop yield and area production at the block level under varying climatic and environmental conditions and policy choices.	Extended-CROPWAT - an extended version of the Food and Agriculture Organisation of the United Nations' (FAO) CROPWAT 4.3 model which has been adapted to include the effects of water and salinity stress, atmospheric fertilisation by carbon dioxide and temperature stress upon crops. Block wise calculations of crop yield and production. Similar to [105,106].	Project analysis
Natural Resources for livelihoods and food security	Aquaculture	Determine the drivers of aquaculture expansion and identify land likely to be converted to aquaculture by 2030	Interviews with large- and small-scale aquaculture farmers to collect data on drivers accelerating the growth of aquaculture, land-use transformation, farming practices, employment generation and profitability.	Primary data



Table 3. Cont.

IAM Framework Sector	Sub Component	Purpose	Model/Data Description	Data Source/Reference
Natural Resources for livelihoods and food security	Mangrove	Determine spatial patterns of mangrove loss and gain (potential recolonisation) under relative sea-level rise and maintenance or removal of embankment scenarios	Sea Level Affecting Marshes Model (SLAMM) v6.7-Simulations based on the latest Digital Elevation Model (DEM) data; a collation of SRTM, Terra-SAR-X and Coastal DEMs, validated and rectified with ground truth data is used to explore inundation and empirical analysis is used to analyse erosion. This will be utilized to explore the possible change in mangrove area within and outside the existing forest area. Similar to [107]	Project analysis
		Explore the effects of climate and anthropogenic stress upon mangrove health	Analysis of trends in historic multispectral and MODIS satellite data in combination with future projections of temperature and rainfall similar to [108].	Project analysis
Poverty and food security outcomes	Economy	Determine current prices of agricultural and fisheries commodities	District statistical handbooks	[109]
		Examine future changes in economic value of goods	Shared Socioeconomic Pathways (version 2.0)	[110]
Poverty and food security outcomes	Multi-dimensional Poverty	Explore spatial and temporal variations in community multi-dimensional poverty.	A statistical model will be used to derive associations between a downscaled multidimensional poverty index and variables related to LULC change, agricultural yield, natural hazard risk, access to urban areas and population density gained from satellite and socio-economic data. Similar to [13,111]	Project analysis
Poverty and food security outcomes	Household survey	Increase understanding of the current socio-economic state of the delta including pattern of livelihood activities and impact of current government policies.	Survey of 1900 households across 19 blocks, stratified to capture diversity according to social vulnerability and proximity to the coast and tidal creeks.	Project analysis
Poverty and food security outcomes	Food Production and Profitability	Examine the magnitude and profitability of food production.	Combined analysis of potential regional food production and market value.	Project analysis

## 5. Discussion/Conclusions

This study used a participatory integrated assessment approach to design an IAM framework to explore socio-ecological interactions related to several SDGs for the Sundarban Biosphere Reserve (SBR), India. The model framework was developed to assess

multiple delta-specific biophysical and socio-economic processes under a range of explorative and/or normative scenarios. The approach adopted is purposely iterative and applied as a learning method that can be updated to incorporate new data, model capabilities, and system understanding as well as evolving stakeholder interests and governance interventions. The participatory nature of the approach ensured that the proposed IAM framework incorporates key processes and model elements of interest to local people and decision makers and represents the relevant linkages between these processes. Policy evaluation informed where mechanisms for exploring potential policy alterations can be best incorporated, while a model and data review allowed the IAM framework to build upon existing capabilities (e.g., [19,33,69]), while innovating to be able to address the SDGs.

Although not fully implemented at present, developing the IAM framework had, on its own, several significant benefits. It provided a focus for discussions that facilitated thinking around linking disparate aspects of the SDGs and a shared tool for enhancing the integration of research, data, and thinking across the different disciplines within the project. Furthermore, the framework created a structure that allowed the exploration of plausible and interesting SDGs' interactions and raised key questions that will provide information that is useful to stakeholders and policy makers.

The IAM framework presented here will be used to explore future interactions (trade-offs and synergies) between the six selected SDGs, as well as strategies for sustainably reducing poverty, improving food security, and conserving biodiversity (in this case the mangrove forests) within the SBR. The IAM will simulate the scenarios of development (Figures 2 and 4) and explore potential policy choices surrounding key issues identified by stakeholders (Table 2). To allow future system changes and policy choices to be assessed in terms of their impacts on SDGs, outputs and knowledge gained from IAM subcomponents will be mapped to specific SDGs. Direct links with SDG targets and indicators can be made to the outputs of several IAM components. For example, outputs from mangrove forest modelling (SLAMM) can be directly linked to SDG indicator 15.1.1: Forest area as a proportion of total land area. Where no direct link with a specific SDG target or indicator can be established, an expert/stakeholder assessment of outcomes on SDG achievement is required [112], such as conversion of land to aquaculture, its implications for sustainable use of land, and its long-term effects on soil degradation (SDG targets 15.1.a and 15.3). The SDGs formally only extend to 2030, but it is often insightful to extend analysis to longer time frames of at least 30 years and potentially even longer, illustrating the contrasting trajectories that emerge due to different development choices and their associated trade-offs and challenges (e.g., [86–88]). For example, the threat of sea-level rise and climate change to the Sundarban mangroves becomes much clearer when we take a 50+-year perspective, and this insight can inform the direction of policy over the next decade and beyond.

The integrated assessment of complex systems is challenging. The primary challenge in the development of this IAM framework was a lack of the region-specific data required to dynamically model several processes of interest. For example, a lack of livelihood data prevents the detailed simulation of human well-being and poverty trajectories, as demonstrated by [113]. Instead, a more empirical approach to the assessment of future state will be used (e.g., understanding changes in multidimensional poverty through its associations with environment). The model and data review highlighted areas where data and/or modelling capability were lacking, such that variables cannot currently be directly simulated and, as such, expert knowledge and additional data collection are required (e.g., soil salinity, population density, access to urban area). In many of these areas, we addressed uncertainties in future conditions within the scenarios of development (Figure 2; Supplementary Information). In other areas, such as seasonal and permanent migration, research was not mature enough to be fully incorporated into the current IAM framework. Identifying these gaps in the assessment is valuable, as it defines the limitations of the framework and identifies areas requiring further research and indicates where the framework could be most usefully expanded in the future. For example, urbanization was highlighted as an important driver of future change by stakeholders and, although partially

addressed in the scenarios of development, the proximity of the SBR to the growing megacity of Kolkata means that areas to the north of this protected region could experience significant and transformative urban development and increased connectivity over the next few decades [23]. Hence, greater understanding of the processes and impacts of urban and peri-urban encroachment into the SBR would be beneficial. Changes in neighboring Bangladesh might also be considered, as the Sundarbans' mangrove forest is contiguous across the border as a globally significant site with important implications for SDG14 and SDG15 in both countries.

The IAM framework described here is novel in that it was developed to analyze SDG interactions at a subnational scale, unlike previous studies, which focused on the national level [91,112]. This subnational level focus is increasingly seen as important as “all of the SDGs have targets directly related to the responsibilities of local and regional governments” [114] (p. 6). The subnational level focus of the overall integrated assessment approach (Section 3) recognizes the complexity and uniqueness of different social-ecological systems (SES) and will provide significant new understanding of local-level implementation of SDG-driven national/state-level policy and their interaction. This approach could be widely applied in other deltas and more broadly in other SES, to address a wide range of questions and issues. By focusing on a specific SES, such as the rural deltaic region of the SBR, the approach and the proposed IAM framework address the issues surrounding how SDG interactions can vary with geographic location and natural resources [2]. They also allow analysis of biophysical and socio-economic processes at scales adequate for a greater understanding of low-level, and potentially unforeseeable or poorly quantified, system interactions. Another advantage is that several of the proposed IAM subcomponents and the interactions between them (e.g., agriculture, aquaculture, urbanization, mangroves, and resulting land-use change and effects on poverty and livelihoods) allow for explicit analysis of spatial variability across the study region, therefore allowing a more nuanced understanding of where and why trade-offs and synergies between SDG thematic sectors occur. The participatory aspect of the integrated assessment ensures that stakeholders can prioritize and explore trajectories for SDG targets that are most relevant to their specific context and needs, which is likely to lead to closer alignment of policy with the UN's 2030 agenda.

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/2073-4447/13/4/528/s1>. Table S1: Stakeholder perception of how driver variables may change going forward to 2050 (Scores are semi-quantitative: 3: very large increase, 2: major increase, 1: some increase, 0: no change, −1: some decline, −2: major decline, −3: very large decline). Scores from four breakout groups (A–D) and the average are shown as well as additional qualitative data recorded. A full narrative description of the four future scenarios developed for the SBR region.

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**Institutional Review Board Statement:** All stakeholders gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki, and the protocol was approved by the Ethics Committee of the University of Southampton (REF: ERGO/FEPS/53020).

**Informed Consent Statement:** Informed consent was obtained from all stakeholders involved in the study.

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